R79-911989-17

14

Evaluation of Basic Laser Welding Capabilities

AD A077575

LEVEL II

Prepared by

D.B. Snow
M.J. Kaufman
C.M. Banas
E.M. Breinan

FINAL REPORT

Contract N00014-74-C-0423

Project No. NR-031-771/5-17-78/471

for

Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

by

UNITED TECHNOLOGIES RESEARCH CENTER

UNITED TECHNOLOGIES

EAST HARTFORD, CONNECTICUT 06108

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: R79-911989-17
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): EVALUATION OF BASIC LASER WELDING CAPABILITIES
5. TYPE OF REPORT & PERIOD COVERED: Final Report. 1 Jun 1974 — 31 May 1979.
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): D. B. Snow, M. J. Kaufman, C. M. Banas, E. M. Breinan
8. CONTRACT OR GRANT NUMBER(s): N00014-74-C-0423
9. PERFORMING ORGANIZATION NAME AND ADDRESS: United Technologies Research Center, East Hartford, CT 06108
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Department of the Navy, Arlington, VA 22217
12. REPORT DATE: July 30, 1979
13. NUMBER OF PAGES: 40
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

Reproduction in whole or in part is permitted for any purpose of the United States Government

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Laser Materials Processing	5456 Aluminum
Laser Welding	5086 Aluminum
Fundamental Studies	Laser Weld Process Feasibility

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

5456 and 5086 aluminum alloys were welded with a continuous, cross-beam CO_2 laser operated in the master oscillator/power amplifier mode (Gaussian beam). Extensive experimental parameter modifications were made to the welding apparatus in an attempt to improve weld quality, in particular the reproducibility and uniformity of fusion zone penetration. The effects of laser (power, mode, optics), process (welding speed, beam rotation, shielding design) and other (weld prep, wire feed, flux, backup, etc.) parameters on weld

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Continued

performance were evaluated. Although some progress was demonstrated, the capability for generation of sound autogenous laser weldments in these alloys on a reproducible basis was not established within the scope of this program. Areas of endeavor which might be expected to produce further significant improvement in the ability to laser weld 5000 series aluminum alloys are not evident at this time.

Accession For
NTIS GRA&I
DDC TAB
Unannounced
Justification
Per ltr on file
By
A

Report R79-911989-17

Evaluation of Basic Laser Welding Capabilities

TABLE OF CONTENTS

INTRODUCTION AND BACKGROUND

This report constitutes the Final Technical Report on Contract N00014-74-C-0423. The work was initiated June 1974 with a study involving the fundamental aspects of laser welding. The objective of this program was to generate information which was relevant to the application of laser welding in manufacturing. Three main tasks were included:

1 - A study of the influence of laser parameters on welding performance.

2 - A study of the effect of the physical properties of metals on their laser welding response.

3 - An attempt to reproduce enhanced weld impact behavior and to investigate the mechanism of fusion zone purification in HY-130 alloy.

During the first year of the program, tasks 1 and 2 were successfully completed and task 3 was begun. The detailed results of these investigations was reported in Ref. 1. This reference reports the effects of welding speed, power, focal length, and laser operating mode on penetration depth and fusion zone cross sectional area. Welding responses (as represented by the dependence of penetration on welding speed) of a wide variety of elemental metals was correlated using a dimensionless empirical relationship involving a speed-related parameter, $V\bar{d}/\alpha$, and a penetration-power parameter, $h\bar{k}\bar{T}m/p$. This correlation is significant in that it permits a priori selection of initial welding parameters for a material if its physical properties and the characteristics of the laser system are known.

Additional information generated during the program included laser energy absorption efficiency and melting efficiency for several elemental metals. Direct calorimetric measurements yielded values from 55 to nearly 90 percent for the former and 24 to in excess of 70 percent for the latter. Melting efficiencies above 50% were identified as theoretically impossible in a published calculation. In view of the experimental data, the prediction was examined, found to be in error, and corrected; improved agreement with experiment was obtained.

Following the fundamental studies described above, attention was directed toward a high yield strength alloy steel of interest to the Navy, namely HY-130. A program was begun to evaluate laser weld performance for refined HY-130 alloy, and continued under future extensions of the contract, as described below.

All work on laser welding and impact behavior of HY-130 alloy steel between November 1975 and February 1977 was performed and is summarized in Ref. 2. Acceptable quality welds with excellent mechanical properties were made in HY-130 steel through 1.27 cm thickness. Weldability of the alloy was found to be improved by better deoxidation practice in the original steelmaking (i.e., rare earth treatment), although substantial elimination of inclusions by the Fusion Zone Purification effect was observed and quantitatively documented in all cases. Toward the end of the successful completion of the experimental work on HY-130, the problems of aluminum alloy laser welding and the effects of welding atmosphere, gas pressure and gas composition became the subjects for the next phases of program investigation.

The third experimental phase of the subject contract began in March 1977. A portion of the results of this phase is contained in Ref. 3.

In this study, detailed analyses were made of the laser weldability of two aluminum alloys, 5456 and 5086. Difficulty was experienced in reproducing weld bead geometries and depths of penetration. Control of the helium shield gas flow rate and flow pattern geometry was observed to be particularly critical for maintenance of full fusion zone penetration in plates of both alloys up to 0.95 cm thickness. 5456 alloy was found to be more easily weldable than 5086, perhaps because of its higher magnesium content. Although full penetration butt welds were achieved in both alloys, drop-through, porosity, and lack of reproducibility remained as severe problems in aluminum welding at the conclusion of that stage of the program. Pertinent observations and conclusions with regard to the state of the art of aluminum laser welding at the start of the present program, included the following:

1. Small changes in both internal and external laser optics and the consequent variations of the energy distribution at the focal point have large effects on the ability of the laser to couple with aluminum alloys and produce deep penetration welds.

2. The energy distribution of the focused, M = 2.0 unstable resonator laser output mode appeared to be more effective in coupling with 5456 and 5086 than a focused Gaussian energy distribution. Typically, coupling with the unstable resonator was accomplished at powers between 2 and 3 kW less than the levels required for an oscillator/amplifier.

3. Inadequate coupling, when experienced, was often accompanied by extensive back-reflection which was potentially damaging to the laser cavity.

4. Despite repeated attempts to measure and control critical parameters including laser output energy, focal plane location, gas shielding geometry, plasma suppression and control, and specimen preparation, substantial variations in coupling occurred.

5. Nonuniform penetration along the weld length was observed in all cases and was attributed to intermittent plasma effects. Efforts to improve plasma suppression lessened but did not eliminate this problem.

6. The exhibited laser weldability of 5456 alloy was substantially greater than 5086.

7. Router finishing with a carbide bit immediately prior to welding was found to produce a clean surface with a reproducible finish on aluminum. This procedure produced improved weld process reproducibility.

8. Penetration and bead appearance were extremely sensitive to small changes in shielding gas flow rate. Best results were achieved with a rapid, steady flow of He gas.

9. Porosity was present in unacceptable amounts in all weld specimens. It was indicated that potential sources of hydrogen bear investigation.

10. All full-penetration welds experienced excessive bead drop-through. This serious problem, which is related to liquid metal viscosity and surface tension,has not been solved.

11. Attempts to solve the problem of drop-through by use of two-sided welding with partial penetration produced improved bead contours but there was excessive root porosity at the base of the second (blind) weld pass.

It can thus be concluded that, upon entering the present stage of the program, substantial problems in aluminum welding remained unsolved, including the lack of reproducibility and ability to control penetration depth, presence of severe porosity, and excessive underbead drop-through. These are basically physical problems, and are believed to relate ultimately to the extreme sensitivity of the aluminum alloys to the intensity of the input energy. In order to produce initial coupling, that is, to overcome the surface reflectivity and penetrate or vaporize the highly stable refractory surface oxide coating and to penetrate the alloy beneath, high power densities are required. Once penetration has been initiated and a "radiation trap" in the form of the deep penetration cavity has been formed, increased energy absorption occurs with excessive penetration, melting, and "drop-through". The high fluidity of the molten aluminum combined with the sensitivity of coupling to energy input have made it very difficult to produce acceptable autogenous weld beads in aluminum alloys while still achieving adequate penetration. The interaction of shielding gas and/or plasma with the beam and workpiece is also a contributing factor, as it adds a built-in variability to the quantity of energy delivered to the workpiece.

Since sound, reproducible welds cannot be formed, it is obvious that studies of weld properties are not justified at this time. Therefore, the program described herein was directed at developing techniques for reproducibly producing acceptable penetration and fusion zone geometries. A secondary goal was the reduction of fusion zone porosity.

DESCRIPTION OF EXPERIMENTS AND RESULTS

The attempts which were made to influence the welding behavior are detailed below. Results of these experimental iterations are also discussed:

1. General
2. Initial Test Series
3. Use of Beam Rotation
4. Use of Weld Backup Plates
5. Gas Shielding Modification for Use with Beam Rotation
   a. Shield Geometry
   b. Gas Shielding Composition
6. Use of Preheat and Flux
7. Use of Wire Feed
8. Two-Sided Welds
9. Additional Attempts to Improve Shielding and Optimize Welding Conditions

1. General Tests

The welding reported herein was performed using the continuous, cross-beam CO_2 laser, mirror train and work station described in Ref. 2. The laser was operated in a master oscillator/power amplifier (MOPA) mode, and produced an approximately Gaussian energy distribution at the beam focal point. The difficulty in achieving adequate coupling of the laser beam with the highly reflective aluminum alloy plate, encountered in the last report (Ref. 3), was eliminated by improvements in beam quality. Modifications were made to the master oscillator to improve mode stability, and existing optics were replaced with cooled, high-quality, gold-coated mirrors. These modifications significantly improved focusing and enhanced laser beam coupling with the aluminum alloys. Coupling was maintained at operating power levels as low as 3 kW. This had not been previously accomplished in any of the tests described in Ref. 3. Consequently it was decided to use this high power, Gaussian output laser and optical system throughout the remainder of the experimental tests.

2. Initial Test Series

The initial experimental tests were made with a fixed shielding enclosure with a cross-flow geometry as shown schematically in Fig. 1. The shield gas composition was either 100% helium or a helium-argon mixture.

Bead-on-plate welds were made in the downhand position on 10.16 x 20.32 x 1.27 cm and 10.16 x 20.32 x 0.64 cm plates of 5456 and 5086 aluminum alloys. The top and bottom surfaces of each specimen were cleaned along the path of the weld seam immediately prior to welding using a portable router with a tungsten carbide bit (Ref. 3). The specimens were placed on a machining table with manual y and z (height) position controls. Welding speed was controlled by traversing the mirror train in the x direction at preselected velocities. The effects of the critical parameters such as beam power, beam traverse speed, shield gas flow rate, shield gas composition, and focal plane location relative to the workpiece, were evaluated by examining the bead-on-plate welds for quality of top bead surface appearance and adequacy of penetration. Two-sided butt welds were attempted only after satisfactory bead-on-plate welds were produced on the same alloy.

Little progress was achieved in improvement of the aluminum alloy laser weld quality due to the repetitive difficulties of spiking (uneven penetration) and excessive drop-through upon full penetration encountered during the initial set of trials (Ref. 3). These problems stem from the specific thermal, optical and physical characteristics of the molten aluminum alloys. For example, the low fluid viscosity at high temperature promotes severe drop-through under penetrating weld conditions.

3. Use of Beam Rotation

Since superheating of the molten aluminum appeared to be a primary cause of weld defects, methods were sought to reduce weld zone temperature. Accordingly, provisions were established for controlled focal spot rotation to promote dispersion of the intense energy input required to ensure coupling. It was presumed that utilization of a rotating spot might provide some of the following advantages.

a. Since aluminum has high thermal diffusivity, solidification occurs rapidly promoting entrapment of generated gases. The rotating focused beam should allow greater specific energy input at decreased weld traverse speeds thereby increasing the local solidification time and producing broader weld zones.

b. Reduced drop-through. Since the rotating beam should decrease the resultant molten metal temperature at a given energy input, excessive drop-through encountered upon full penetration in previous weld trials might be reduced.

c. Improved top surface bead characteristics. Since surface bead defects appear to be associated with local vaporization, the rotating beam might eliminate the violent eruptions on the top surface by effectively smoothing out the molten aluminum pool and reducing its temperature.

To evaluate these potential advantages, a beam rotating device was incorporated in the focusing optics as shown in Fig. 2. This unit provided controlled spot rotations on selected radii at rotational speeds to 5000 rpm.

It was found that the rotating spot diameter and speed were critical parameters affecting the quality of the welds produced as noted in Table 1 and throughout the experimental trials and as summarized below:

1. The coupling efficiency decreased with increased rotational speed and spot diameter at the same traverse velocity, shielding arrangement and focal plane position.

2. The depth of penetration decreased with increased rotational speed and spot diameter at the same traverse velocity, shielding arrangement, and focal plane position.

3. The weld quality was generally better at the higher rotational velocities and, though optimum settings were never established, was best at a ratio of rotational speed to traverse speed of approximately 100 to 1 (e.g. 3000 rpm and 1.27 cm/s (30 in/min)).

4. The ability to control the flow of the highly fluid molten aluminum, and thus the weld bead itself, was very dependent on the diameter of the spot rotation. This critical parameter was optimum in the range from 0.25 to 0.40 cm but was dependent on other operating parameters.

Single pass bead-on-plate welds in 0.64 cm thick plate and two-sided butt welds in 1.27 cm plate, after bead-on-plate welds proved satisfactory, were made using the rotating mirror system coupled with the cross-flow shielding geometry (Table I). Subsequently, metallographic analysis and radiographic examination were performed on selected welds (Figs. 3-7). Figures 3-5 clearly demonstrate the problems of uneven weld contour due to the rotating beam, spiking tendencies, and excessive amounts of weld porosity repeatedly encountered during the weld tests. Figures 6 and 7 show two-sided butt welds produced with the rotating beam which are considerably superior to those made without it (Figs. 13 and 14, Ref. 3).

4. Use of Weld Backup Plates

The use of backup plates was identified as another possible means of controlling the excessive drop-through which was continually experienced upon full penetration. The extreme variations in the absorptivity of different materials for CO_2 laser radiation resulted in difficulty in selecting a suitable material for this purpose. Copper was ultimately chosen as a candidate material, since it behaves similarly to aluminum when exposed to CO_2 radiation, and plates were machined for this purpose. Numerous welds were made (Table II) using the backup plates with no improvement in weld quality (Fig. 8). The backup plates enhanced gas pickup and consequent weld porosity due to the difficulty in supplying a sufficient protective atmosphere to the bottom surface. Also, contamination of the weld by backup material occurred due to beam interaction with the backup plate.

5. Gas Shielding Modifications for Use with Beam Rotation

A serious problem was encountered in this phase of the program with the system of rotating beam and cross-flow shielding. This gas shield geometry was the most effective of all previous weld trials to date, in inhibiting gross plasma formation and weld metal oxidation at the high traverse speeds usually encountered. But, by employing the rotating beam, which was accompanied by a decrease in traverse velocity and an increase in the liquid state duration within the weld pool, the high gas flow rates required with the cross-flow shield resulted in the actual physical removal of the molten aluminum from the weld pool. This difficulty was attributed to the physical characteristics, low density and viscosity, of the liquid aluminum alloys. Welds were then made at reduced gas flow rates and the weld quality decreased with decreasing gas flow rate.

a. Shield Geometry

A new and simple "gas lens" jet was then designed and implemented into the welding system to alleviate the liquid aluminum displacement problem. It consisted of a 2.54 cm diameter copper cylinder directed at the workpiece interaction point at an angle of approximately 45^{o} to the workpiece as shown with the welding system in Figs. 9 and 10. This new geometry effectively directed a large quantity of shielding gas toward the beam workpiece interaction point in a direction opposite the weld traverse direction. This new design was effective in inhibiting gross plasma formation and bead oxidation under the proper operating conditions. Also it enabled the experimenter to directly observe the welding process thereby providing an indication of possible parameter modifications.

b. Gas Shielding Composition

Various argon-helium shielding mixtures were employed with the new gas shielding (Table III). It was found that 100% helium was the most effective for aluminum welding as was found with most previous shielding arrangements.

Numerous weld tests were performed with the above system and are tabulated in Table IV. Significant progress was made in the ability to control weld quality. Spiking, though not eliminated, was considerably reduced over previous trials. Also, the problem of excessive drop-through, and accompanying gross undercut, upon full penetration was found to be controllable by utilizing the proper rotation-speed, traverse-velocity combinations. However, lack of reproducibility of welding results was continuously noted. This indicated that some variation in material or experimental conditions was effectively occurring. The two areas which were considered most difficult to quantitatively monitor are the detailed nature of the laser beam itself (energy distribution at the focal point and mode purity) and the specific behavior of the gas shielding configurations. The variation in these parameters was observed to be quite critical to the welding performance, as noted previously.

6. Use of Preheat and Flux

Various other experiments were performed in attempts to improve weld quality. These included preheating the aluminum plates and fluxing the aluminum prior to welding. Preheating the workpiece to 150°C prior to welding would conceivably decrease the rate of solidification of the liquid aluminum and allow greater flow in the weld pool thus producing a smoother weld bead and reduce porosity. Little success was achieved (Table V, run 3-26) and this method was not further pursued. The introduction of flux onto the surface of the aluminum plate to be welded in an attempt to increase the coupling efficiency, promote wetting and reduce contamination also proved to be ineffective (Table V, runs 3-18, 3-19, 3-20, 2-17, 2-18). The flux reacted violently with the laser beam and gas shielding atmosphere and enhanced gross plasma formation which was accompanied by unacceptable weld appearance and porosity levels.

7. Use of Wire Feed

Though the weld quality was improved considerably, by using the rotating beam/gas lens combination, upon full penetration the top bead surface contained a slight undercut on one side of the weld bead relative to the other. This phenomenon was attributed to the variation in the laser beam velocity relative to the workpiece due to the beam rotating and traversing the workpiece. Simultaneously, beam rotation causes a continuous change in instantaneous relative velocity of the beam and workpiece; a relative velocity of zero may occur at one point in the motion. Wire feeding was employed in an attempt to reduce or possibly eliminate this problem and is shown with the welding system in Figs. 9 and 10. Several bead-on-plate welds were made on 0.64 cm plate incorporating the wire feed speed as an extra parameter (Table VI). Metallographic and radiographic analysis of selected welds (Figs. 11-16) demonstrated near porosity free welds with fairly uniform penetration. Examination of the transverse weld sections (Figs. 14-16) showed that although the top bead unevenness was reduced it was not completely eliminated by employing wire feed. Additional evaluation appears warranted.

8. Dual Pass Welds

Though welding with continuous filler wire addition yielded promising results, it was considerably more tedious than direct autogenous welding. This factor and the improved bead characteristics obtained in shallow, nonpenetrating welds led to the decision to generate dual pass welds.

The remainder of the experimental tests were performed making bead-on-plate penetrations on 1.27 cm plate until weld appearance was acceptable and, subsequently, using the exact same conditions, welding 0.64 cm plate to check for adequate depth of penetration. If penetration was found to be adequate, then two-sided butt welds were made on 1.27 cm plate without purposely altering any operating parameters. Numerous tests were made with little success achieved in producing acceptable butt welds (Table VII) Difficulties were continuously experienced when attempting to produce acceptable two-sided butt welds after acceptable bead-on-plate welds were achieved on the same alloy, and presumably using the same operating conditions (Table V, runs 5-24, 6-17, 6-21, 6-35).

9. Additional Attempts to Improve Shielding and Optimize Welding Capabilities

In the final phases of the aluminum alloy welding program, efforts were concentrated on improving shielding geometry, an extremely critical parameter affecting weld quality in all previous experimental trials. The welding system was returned to the cross-flow gas shield/rotating beam setup described earlier and numerous weld trials were performed (Table VIII). The gas-flow rate was lowered, below previous trials, to avoid removal of liquid aluminum from the weld pool. Pool disturbance was eliminated under a variety of parameter settings. However, little progress was made in producing higher quality welds.

The rotating mirror system was modified for easier adjustment of the rotating spot diameter. This modification was accompanied by thorough cleaning of the turning mirror and focusing mirror and precise beam realignment. These adjustments caused a considerable increase in beam power and coupling ability. Coupling was achieved at 3 kW, a power level at which coupling had never before been achieved in any aluminum laser welding test (Table IX, runs 11-15 and 11-16).

Several weld trials were made after the above modifications were performed (Table IX). Again acceptable welds were not formed even with the wide variety of changes in operating parameters.

Next the 2.54 cm diameter copper gas lens was reinstalled in place of the cross flow shield. Several weld tests were made with little improvement in welding ability (Table X). Laser coupling ability and weld bead contour continued to be extremely difficult to control. The welds were consistently uneven in appearance regardless of the parameter adjustments. In an effort to alleviate this phenomenon the rotating spot diameter was increased from 0.19 cm to 0.31 cm. A series of weld tests were then made with no success in reducing bead nonuniformity regardless of the operating conditions (Table X, runs 11-28 through 11-37).

At the end of the laser welding aluminum investigation described herein, a new and promising modification of the copper gas lens was designed and implemented into the system. It consisted of a 2.54 cm diameter, copper cylinder, as before, but extending into the path of the beam. A hole was drilled in the top side for laser beam passage. The difficulty encountered upon welding was that as the beam traversed the specimen the back reflected portion of the incident radiation struck the shield and resulted in rapid heating and ultimately melting of the shield. Since the weld quality was somewhat improved using this new design over previous designs, it was suggested water cooling the shield as a possible alternative. Future investigation may involve such a modification.

SUMMARY OF PERTINENT OBSERVATIONS AND CONCLUSIONS

1. Improved laser beam quality and focusing, regardless of the operating mode, improves coupling ability with the aluminum alloys.

2. The rotating laser beam focal spot improved aluminum welding capability. It allowed greater specific energy input and consequently increased the local solidification time. It also reduced drop-through, associated with full penetration, by reducing molten metal temperature.

3. The best results in this program were obtained with a ratio of beam rotation velocity to weld speed approximately 100:1. Additional optimization tests are required.

4. The use of backup plates is an unacceptable technique for controlling laser weld drop-through in full penetration. Use of backup complicates bottom surface atmospheric protection and also leads to root bead contamination by backup material.

5. Small changes in shielding gas flow or composition resulted in substantial changes in weld bead appearance and penetration indicating the criticality of shielding in the laser welding process. Fairly high flow rates of pure helium appeared to produce the best results.

6. Gas shield geometry is a critical factor in making acceptable welds in aluminum alloys. The criticality was attributed to the physical characteristics, low density and viscosity, of the aluminum alloys. Further development of shielding provisions is desirable.

7. Conventional techniques sometimes used in welding aluminum alloys, such as preheating or use of a welding flux, do not appear to be useful in laser welding. Preheating, apart from driving off possible absorbed moisture, does not seem to influence the laser welding process presumably due to the rapid energy exchange involved. Conventional flux, which contains negative ion formers suitable for arc stabilization, promotes plasma formation and is totally incompatible with the laser process.

8. Filler wire addition was required in all single pass, through penetration welds using the rotating mirror system to eliminate local top bead underfill.

9. Metallographic and radiographic analysis of some of the laser welds demonstrated acceptable porosity levels for single-pass, through penetration conditions. Dual-pass, although exhibiting smoother surface beads, contained excessive root porosity at the base of the second (blind) weld pass.

10. The focal plane position produces varied results in the ability of the laser beam to couple with the aluminum alloys and produce sound welds. The optimum focal plane location was found to depend on the laser output power, weld speed, and velocity of beam rotation.

11. Random variations in coupling were encountered. The cause of these variations has not been satisfactorily resolved but depends strongly on laser power focal plane position, shielding gas composition, shielding geometry, specimen preparation, rotating focused spot diameter and speed of beam rotation.

REFERENCES

1. Breinan, E. M. and C. M. Banas: Evaluation of Basic Laser Welding Capabilities. Technical Report R76-911989-4, Contract N00014-74-C-0423, United Technologies Research Center, East Hartford, CT, Nov. 1975.

2. Breinan, E. M., C. M. Banas, G. P. McCarthy and B. A. Jacob: Evaluation of Basic Laser Welding Capabilities. Technical Report R77-911989-10, Contract N00014-74-C-0423, United Technologies Research Center, East Hartford, CT, March 1977.

3. Snow, D. B. and E. M. Breinan: Evaluation of Basic Laser Welding Capabilities. Technical Report R78-911989-14, Contract N00014-74-C-0423, United Technologies Research Center, East Hartford, CT, July 1978.

Table I

Initial Laser Bead-on-Plate Welds of 0.64 cm Plate After Introduction of Rotating Beam, Cross-Flow Shield, Oscillation/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium* Flow Rate (cm^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Comments
131-1	x		6.0	2.12	1.46/2.83	0.36	1500	No penetration
131-2	x		"	2.12	1.13/2.26	-	0	Intermittent holes
131-5	x		"	1.91	1.46/2.83	0.36	1350	No penetration
131-6	x		"	1.69	"	"	2000	Poor coupling
131-8	x		7.0	1.48	"	"	2100	Poor coupling
131-11	x		"	1.69	"	"	600	Heavy penetration
131-13	x		"	2.54	"	"	600	Better, full penetration
131-14	x		"	2.96	"	"	700	Uneven penetration
131-16	x		"	2.54	"	"	900	Little coupling
131-18	x		"	2.12	"	"	750	Uneven penetration
131-19	x		"	1.69	"	"	1200	No penetration
131-24	x		"	2.12	"	"	900	Intermittent penetration
134-1	x		8.0	2.12	1.70/1.70	0.36	1000	Fair weld bead
134-3	x		"	2.54	"	"	1200	Poor weld
134-5	x		"	2.54	2.26/2.83	-	0	Heavy penetration, oxidized bead
134-7	x		"	3.60	2.83/2.83	-	0	Heavy plasma generation
134-9	x		7.0	3.18	3.40/2.83	0.36	1200	No coupling
134-12	x		"	1.69	"	"	1200	No coupling

*cross flow/trailer flow

Table II

Laser Bead-on-Plate Weld Series Using Copper Backup Plates, 0.64 cm Plate
Cross-Flow Shield, Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium* Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Comments
131-25	x		7.0	2.12	0.99/1.42/2.83/0.42	0.36	750	Full penetration-good bead
132-1	x		"	2.54	0.99/1.42/2.26/0.42	"	1200	Intermittent penetration
132-3	x		"	2.12	0.99/1.13/2.83/0.42	"	1200	Heavy underbead
132-4	x		"	2.12	"	"	1500	Good overhead, no penetration
132-5	x		"	1.69	"	"	1500	Very little coupling
132-6	x		"	2.54	"	"	2000	Little penetration
132-11	x		"	3.60	"	-	0	Heavy penetration
132-12	x		"	4.23	"	-	0	Full penetration
133-17	x		"	2.54	0.99/0.85/2.83/0.84Ar	0.36	2400	Narrow bead, no penetration
133-18	x		"	2.54	"	"	2400	No penetration
133-19	x		"	2.54	"	"	1200	No penetration
133-22	x		"	1.69	0.99/1.46/2.83/1.56Ar	"	800	Underbead drop-through
133-23	x		"	1.69	"	"	2000	Partial penetration
133-24	x		"	1.27	0.99/0.85/2.83/1.56Ar	"	3000	No penetration, pool forced to one side
133-25	x		7.0	1.27	0.99/[illegible]/2.83/1.56Ar	0.36	600	Heavy underbead; overbead underfill
133-26	x		5.0	1.27	0.99/0.57/2.83/1.56Ar	"	300	Fair, some holes
133-28	x		4.5	1.06	0.99/0.57/2.83/1.46Ar	"	1000	Smooth overbead, no penetration
133-34	x		3.5	1.06	"	"	250	No penetration
133-37	x		4.0	1.27	0.99/0.57/2.83/1.46Ar	0.36	500	Partial penetration
141-1	x		6.0	1.27	0.99/1.70/2.83/1.13	0.25	3000	Overbead undercut, no penetration
141-3	x		6.0	1.69	"	"	4000	"
141-5	x		5.0	1.48	"	"	3500	Slight penetration, severe undercut
141-6	x		4.0	1.06	"	"	5000	No coupling
141-10	x		5.0	1.27	"	0.32	1500	Better overbead, no penetration
141-11	x		"	1.06	"	"	500	Undercut overbead, incomplete penetration
141-12	x		"	1.06	0.85/1.13/2.83/1.13	"	500	No appreciable change
141-13	x		"	1.69	"	"	2000	No penetration

*forward flow/cross-flow/trailer flow/backup shield flow

Table III

Laser Weld Tests Varying Shielding Gas C[illegible]position, 0.64 cm Plate Copper Gas Lens Shield, Oscilla[illegible] - Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Gas Flow Rate (m^3/hr) Helium	Gas Flow Rate (m^3/hr) Argon	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Comments
3 24	x		7.0	1.48	2.83	2.83	0.32	3000	Some plasma generation, intermittent penetration
3-25	x		"	1.27	"	"	"	"	More plasma generation, intermittent penetration
4-11		x	6.0	1.48	0	"	"	3600	Very much plasma generation
4-12		x	"	"	1.42	"	"	"	"
4-13		x	"	"	2.83	2.26	"	"	Some plasma generation but much better

Table IV

Laser Bead-on-Plate Weld Series After Introduction of Copper Gas Lens Shield 0.64 cm Plate, Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Comments
143-1	x		5.0	1.69	2.83	0.18	2000	Undercut weld bead
143-3	x		"	2.12	"	"	2500	Intermittent penetration
143-4	x		4.0	1.27	"	"	3000	No coupling
143-6	x		5.0	1.69	"	0.26	2000	No penetration
143-8	x		"	"	"	"	2000	Focal plane lowered 0.381 cm, improved, better penetration
143-10	x		"	"	"	"	1500	Better penetration
143-11	x		"	1.48	"	"	1000	Undercut weld bead, plasma generation
143-13	x		"	1.69	"	"	500	Undercut weld bead
143-14	x		"	"	"	"	1000	Intermittent penetration
143-15	x		6.0	"	"	"	1000	Drop-through of weld bead
143-16	x		"	"	"	"	2000	Spotty penetration
144-23	x		4.0	1.69	2.83	0.26	2000	Clean bead but no penetration
144-24	x		4.0	1.27	2.26	"	3000	Much plasma generation
144-25	x		5.0	1.69	2.83	"	4000	No penetration, uneven overbead
144-1	x		5.0	1.69	2.83	0.32	2000	Oxidized, undercut weld bead
144-2	x		"	1.69	5.66	"	3000	Clean bead, no penetration
144-6	x		"	1.27	"	"	2500	Undercut weld bead
144-9	x		"	1.27	"	"	4000	Intermittent penetration
144-12	x		"	1.48	"	"	3000	Intermittent penetration
144-13	x		7.0	2.12	"	0.38	2000	Good overbead, no penetration
144-14	x		"	3.82	"	-	0	Traces of penetration
146-10	x		7.0	1.69	5.66	0.38	2000	Narrow bead, full penetration
146-11	x		"	1.69	"	"	5000	Partial penetration
146-12	x		"	1.61	"	"	3000	Good underbead and overbead
146-13	x		"	1.61	"	"	3000	Butt weld, slightly uneven weld bead
146-14	x		"	1.27	"	"	4000	Very uneven weld bead

Table V

Laser Bead-on-Plate Weld Tests Using Preheat and Aluminum Welding Flux Techniques
5086 Alloy, 0.64 cm, Copper Gas Lens Shield, Oscillator/Amplifier Mode

Run	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Preheat Temp. (^oC)	Flux	Comments
3-26	7.0	1.48	4.25	0.32	3000	150		Good underbead, overbead underfilled, same as without preheat
3-18	5.0	1.27	5.66	"	"	-	x	Very good coupling, plasma generation, uneven oxidized bead
3-20	"	2.12	"	"	3600	-	x	Good coupling, no penetration
2-17	7.0	1.07	"	0.42	3000			Full penetration, uneven and oxidized weld bead
2-18	"	1.27	"	"	"	-	x	Fluxed on one side only, full penetration with gross oxidized underbead

Table VI

Laser Bead-on-Plate Welds of 0.64 cm Plate using Wire Feeder, Copper Gas Lens Shield, Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Wire Feed Velocity (cm/s)	Comments
1-4	x		7.0	1.27	5.66	0.32	3000	4.23	Wire welded to plate
1-6	x		"	"	"	"	"	3.39	Full penetration, uneven bead
1-8	x		"	"	"	"	"	2.12	Better, overbead slightly underfilled
1-9	x		"	1.07	"	"	5000	3.39	Very large underbead
1-11	x		"	1.27	"	"	3000	4.23	Good weld, overbead slightly underfilled
1-12	x		"	1.48	"	"	"	"	Better, uniform underbead and overbead
1-13	x		"	1.69	"	"	"	"	Irregular underbead, good overbead
1-14	x		"	"	"	"	"	4.87	Wire feed malfunction
1-15	x		"	"	"	"	800	4.23	Large plasma generation, very uneven weld
1-16	x		"	"	"	"	1500	"	Plasma generation, uneven weld bead
1-18	x		"	"	"	"	2500	"	Better but still uneven
2-1	x		"	"	"	"	3000	3.81	No penetration
2-2	x		"	1.48	"	"	"	"	Full penetration, slightly uneven weld bead
2-3	x		"	1.27	"	"	"	6.35	
2-3	x		"	1.27	"	"	"	6.35	Very irregular well bead
2-4	x		"	"	"	"	"	5.08	Wire feed malfunction
2-5	x		6.0	1.07	"	"	3600	"	Very uneven weld bead
2-6	x		"	1.27	"	"	"	4.23	Decreased angle of shield to 25°
2-7	x		"	"	"	"	"	"	Good weld for 4.5 cm along length
2-10	x		5.0	"	"	"	3000	3.39	Very uneven weld bead
2-11	x		8.0	"	"	0.42	"	"	Uneven weld bead
2-12	x		"	1.69	"	"	"	"	Intermittent penetration
2-14	x		"	1.48	"	"	"	"	Full penetration, uneven weld
2-16	x		7.0	1.27	"	"	"	4.23	No penetration
3-9	x		6.0	"	"	0.32	"	"	Very uneven overbead and underbead
3-10	x		"	1.19	"	"	3600	"	Intermittent penetration
3-12	x		6.5	"	"	"	"	"	Full penetration, too much drop-through
3-17	x		5.0	1.27	"	"	120	"	Very uneven weld bead
4-1	x		7.0	1.48	"	"	3000	"	Uneven underbead
4-2	x		"	"	"	"	3250	"	Intermittent penetration
4-3	x		"	1.35	"	"	3500	"	Intermittent penetration
4-27	x		"	1.27	4.25	"	3000	"	Uneven underbead

Table VII

Laser Bead-on-Plate and Butt Welds of 1.27 cm and 0.64 cm plate, Copper Gas Lens Shield, Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium Flow Rate (m /hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Plate Thickness (cm)	Bead on Plate	Bead on Butt	Comments
3-14		x	6.5	1.48	5.66	0.32	3600	1.27	x		Good weld bead, slightly uneven
3-16		x	"	1.69	"	"	3000	"	x		Very uneven weld
4-5		x	7.0	1.48	4.95	"	3600	"	x		Uneven weld bead
4-6		x	"	1.69	"	"	"	"	x		Worse
4-8		x	"	1.48	"	"	"	"	x		Focal plane raised 0.13 cm still uneven
4-10		x	6.0	"	5.66	"	"	"	x		Slightly uneven bead
4-14		x	"	"	"	"	5000	"			Worse
4-15		x	"	"	"	"	3600	"	x		Focal plane lowered 0.38 cm, much plasma generation
5-16		x	"	"	1.42	"	"	"	x		Much plasma generation
5-17		x	7.0	1.27	4.95	"	3000	"	x		Decreased angle of gas lens to 30°, better but slightly uneven
5-19		x	"	1.48	5.66	"	"	"	x		Gas lens at 45°, uneven weld bead
5-20		x	"	1.69	"	"	"	"	x		Very uneven weld bead
5-21		x	"	"	"	"	1500	"	x		Much plasma generation
5-23		x	"	1.27	"	"	3000	"	x		Uneven weld bead
5-24		x	"	1.48	"	"	"	"		x	1st pass: good overbead 2nd pass: good overbead lack of root penetration
6-3		x	"	"	"	"	"	"	x		Uneven weld bead
6-4		x	"	1.69	"	"	"	"	x		Better but slightly uneven
6-6	x		"	"	"	"	"	0.64	x		Intermittent penetration
6-7	x		"	1.48	"	"	3500	"	x		Even penetration, sharp notch along one side of underbead
6-8	x		"	"	"	"	3000	"	x		Good underbead, smaller depth of penetration
6-9	x		6.5	"	"	"	3500	"	x		Good even weld
6-10		x	"	"	"	"	"	1.27	x		Very uneven weld
6-11		x	"	"	"	"	"	"	x		Focal plane raised 0.25 cm, better
6-12		x	"	"	"	"	"	"	x		Focal plane raised 0.25 cm, still slightly irregular
6-13		x	7.0	"	"	"	3000	"	x		Much better
6-14		x	"	"	"	"	"	"	x		Focal plane raised 0.13 cm, little coupling
6-15		x	"	"	5.10	"	"	"	x		Very good weld bead
6-16	x		"	"	"	"	"	0.64	x		Good full penetration weld bead
6-17		x	"	"	"	"	"	1.27		x	Very uneven bead, much plasma generation and weld splatter
6-19		x	"	"	"	"	"	"	x		Focal plane lowered 1.66 cm, very uneven weld bead
6-22	x		"	"	5.66	"	"	0.64	x		Focal plane raised 1.02 cm, better, fairly even weld bead
6-23	x		"	"	"	"	"	"	x		Focal plane dropped 0.25 cm, overbead has slight underfill along one side
6-24	x		"	"	"	"	"	"	x		Focal plane lowered 0.25 cm, good weld
6-25		x	"	"	"	"	"	1.27		x	1st pass: very uneven bead 2nd pass: better
6-29		x	"	1.69	"	"	"	"	x		Uneven weld bead
6-30		x	"	1.91	"	"	"	"	x		Good weld bead with sufficient depth of penetration
6-31		x	"	"	"	"	"	"		x	1st pass: very uneven bead 2nd pass: slightly more even
8-33		x	6.0	1.27	"	0.34	"	"	x		Very uneven weld
8-34		x	"	"	"	"	5000	"	x		Good, even weld
8-35	x		"	"	"	"	"	0.64	x		No penetration
8-36	x		8.0	"	"	"	"	"	x		Full penetration, good even weld

Table VIII

Laser Bead-on-Plate Weld Tests Cross Flow Shield,
Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium* Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Plate Thickness (cm)	Comments
8-2		x	6.0	1.27	1.42/2.26	0.33	3000	1.27	Uneven weld bead, groove along bead center
8-4		x	"	"	"	"	300	"	Better, slightly uneven
8-5	x		"	"	"	"	"	0.64	Full penetration, slightl; oxidized underbead
8-6		x	"	"	0.71/2.55	"	"	1.27	Uneven weld bead
9-7		x	"	"	0.57/2.55	"	3000	"	Better, slightly uneven
9-9		x	"	"	0/2.55	"	"	"	Very uneven weld bead
9-10		x	"	"	0.71/2.83	"	450	"	Uneven weld bead, under-fill along one side
9-12		x	"	"	"	"	600	"	Focal plane raised 0.25 cm, uneven weld bead
9-13		x	5.5	"	"	"	"	"	Focal plane lowered 0.13 cm, initial problem coupling
9-14	x		5.0	0.85	0.28/2.83	"	3000	0.64	No penetration
9-15		x	8.0	1.69	"	"	"	1.27	Focal plane lowered 1.02 cm, good even weld bead
9-16		x	"	2.54	"	"	"	"	Focal plane raised 0.64 cm, uneven weld bead
9-17		x	"	1.69	1.42/2.83	"	"	"	Uneven weld bead
9-18		x	"	2.96	"	-	0	"	Very uneven weld bead

*cross flow/trailer flow

Table IX

Laser Bead-on-Plate Weld Test Series After Cleaning and Realigning Laser Optics System, Cross-Flow Shield, Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium* Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Plate Thickness (cm)	Comments
10-1		x	6.0	1.27	1.13/2.83	0.19	3000	1.27	Very uneven bead, intermittent deep craters
10-2		x	"	"	"	"	"	"	Focal plane lowered 0.51 cm, intermittent full penetration
10-4		x	"	2.54	"	"	"	"	Very uneven bead, deep penetration
10-5		x	"	3.18	"	"	"	"	Narrow, uneven weld bead
10-7		x	4.0	1.27	"	"	"	"	Very uneven bead with intermittent craters
10-9		x	"	1.48	0.57/2.83	"	300	"	Worse, very uneven
10-10		x	"	"	1.13/2.83	"	5000	"	Uneven weld bead, some intermittent craters
11-11		x	"	"	1.70/2.83	"	3000	"	Removal of molten aluminum from weld pool by gas flow
11-12		x	"	"	0/2.83	"	"	"	Very uneven weld bead, intermittent craters
11-14		x	4.3	"	0.57/2.83	"	"	"	Focal plane lowered 0.51 cm, fairly even weld bead with few craters
11-15		x	3.0	1.07	"	"	"	"	Good overbead but inadequate penetration
11-16		x	"	0.64	"	"	"	"	"

*cross flow/trailer flow

Table X

Laser Bead-on-Plate Weld Tests on 1.27 cm Plate After Cleaning and Realigning Laser Optics System, Copper Gas Lens Shield, Oscillator/Amplifier Mode

Run	Alloy 5086	Alloy 5456	Set Power (kW)	Beam Traverse Velocity (cm/s)	Helium Flow Rate (m^3/hr)	Rotating Spot Diameter (cm)	Rotating Spot Velocity (RPM)	Comments
11-23		x	6.0	1.69	2.83	0.19	3000	Uneven bead, intermittent holes
11-25		x	"	"	4.25	"	"	"
11-26		x	"	2.12	5.10	"	"	Better, some metal removal by gas
11-27		x	"	"	5.66	"	"	Worse, very uneven, large craters
11-28		x	"	1.27	2.83	0.31	"	Initial plasma formation, little coupling
11-29		x	"	"	4.25	"	"	Uneven bead, intermittent holes
11-30		x	"	"	"	"	300	Uneven weld bead
11-31		x	"	"	"	"	100	Slight improvement
11-32		x	5.0	"	"	"	1200	More even, shallow, intermittent craters
11-33		x	"	"	"	"	2400	Very little coupling
11-35		x	10.0	3.39	"	"	4000	Large plasma generation, uneven weld bead
11-36		x	"	"	"	"	"	Focal plane raised 0.51 cm, worse, large craters
11-37		x						Smooth overbead but little penetration

R79-911989-17

INERT GAS PLASMA SUPPRESSOR AND WELD SHIELD

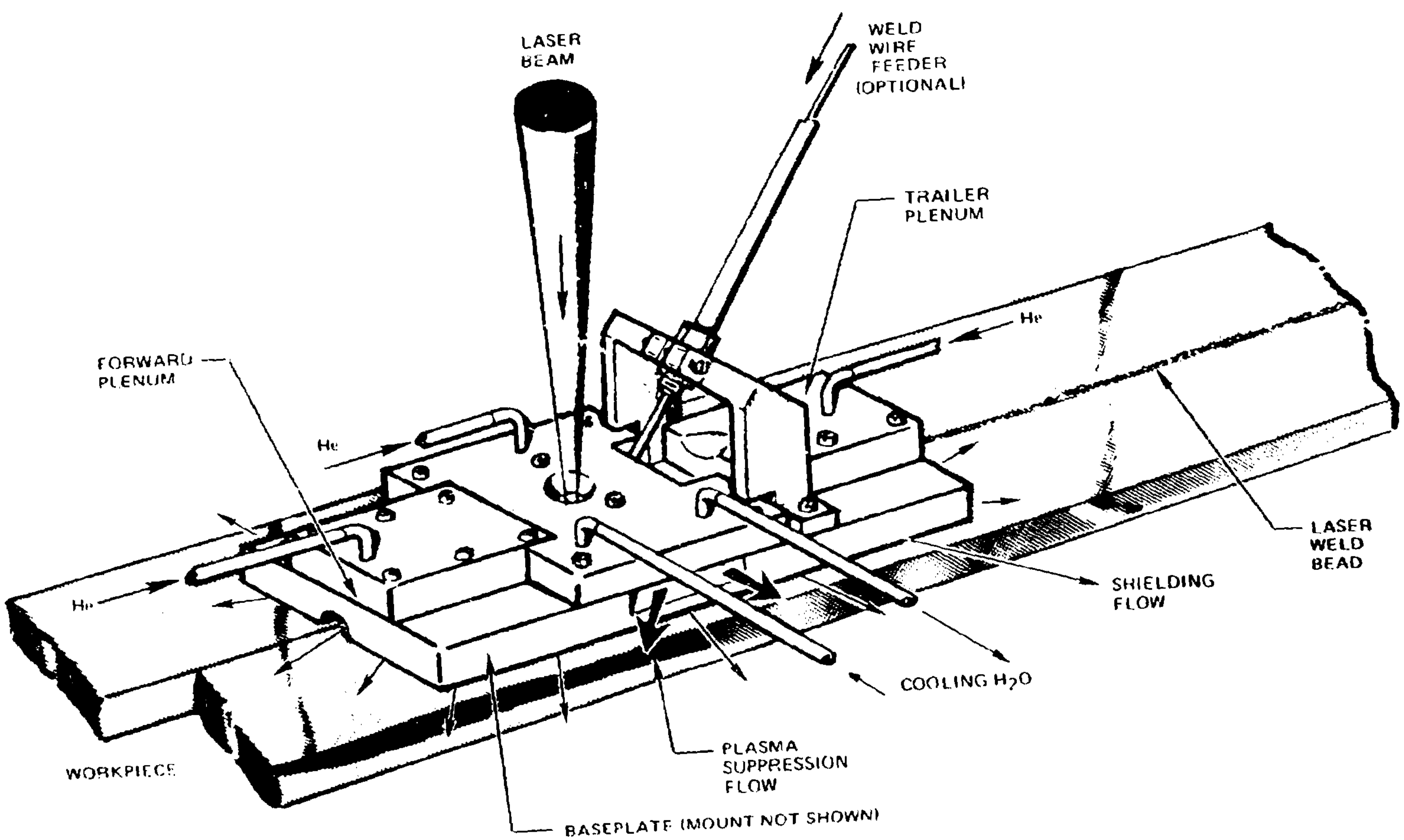
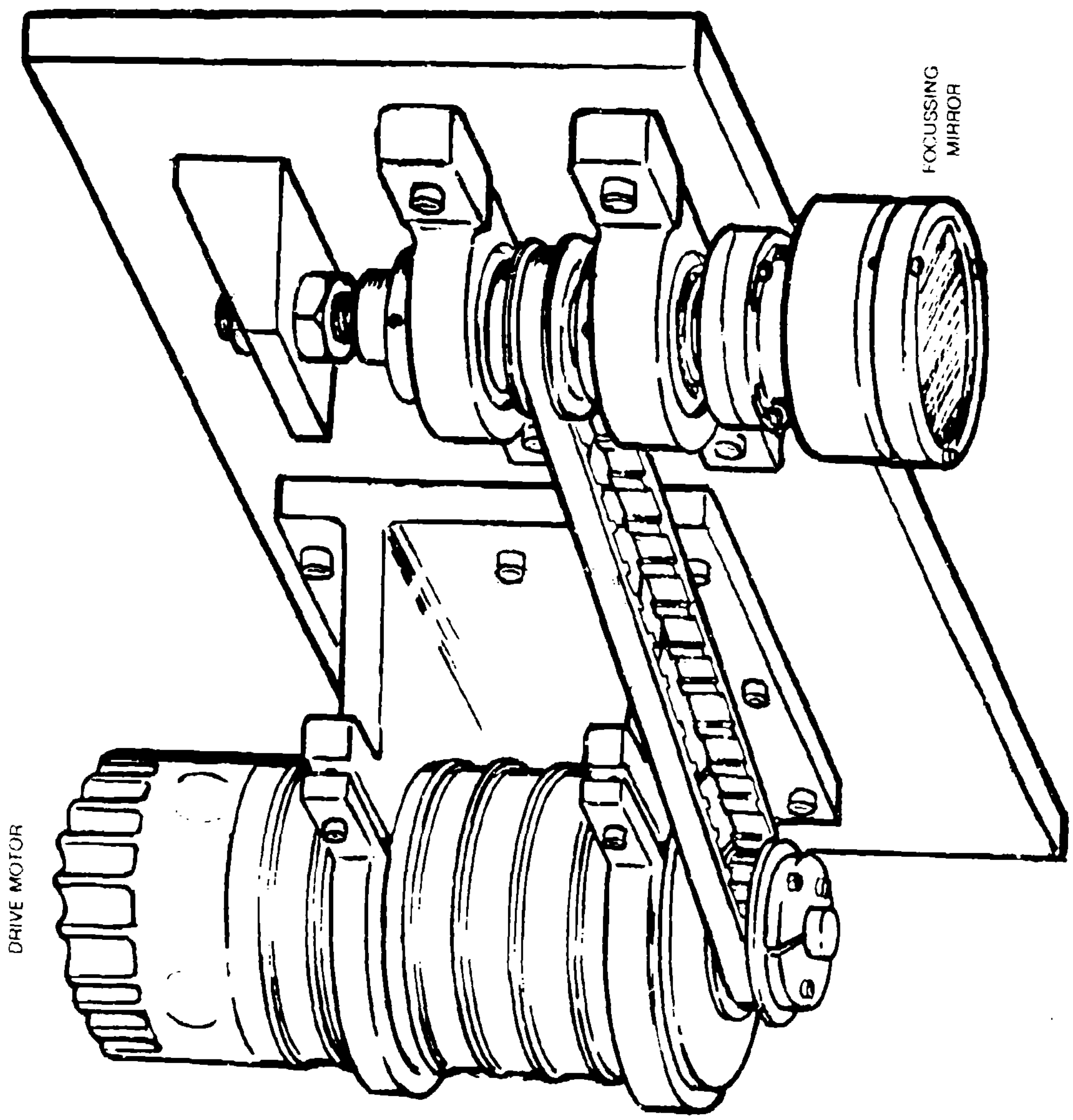


FIG. 1

79 05 7..1

FIG. 2

LASER BEAM ROTATION SYSTEM

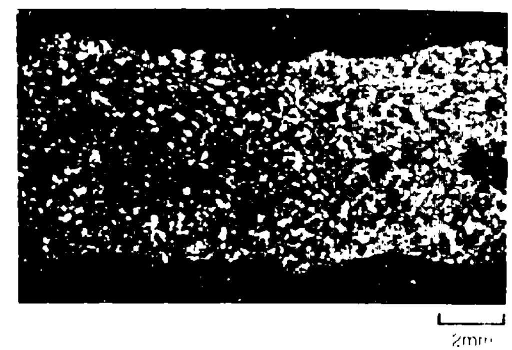


78-08-72-1

STRUCTURE OF WELD 133-28

TABLE II BEAD-ON-PLATE 0.64cm 5086 4.5kW 1.06 cm/s 1000 RPM

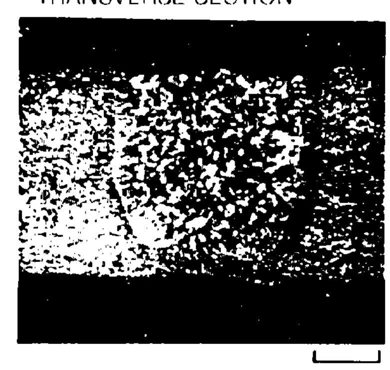
C WELD MICROSTRUCTURE
LONGITUDINAL SECTION



A WELD BEAD SURFACE

← LASER BEAM TRAVERSE DIRECTION

D WELD MICROSTRUCTURE
TRANSVERSE SECTION



B RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

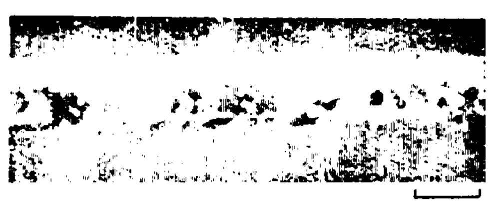
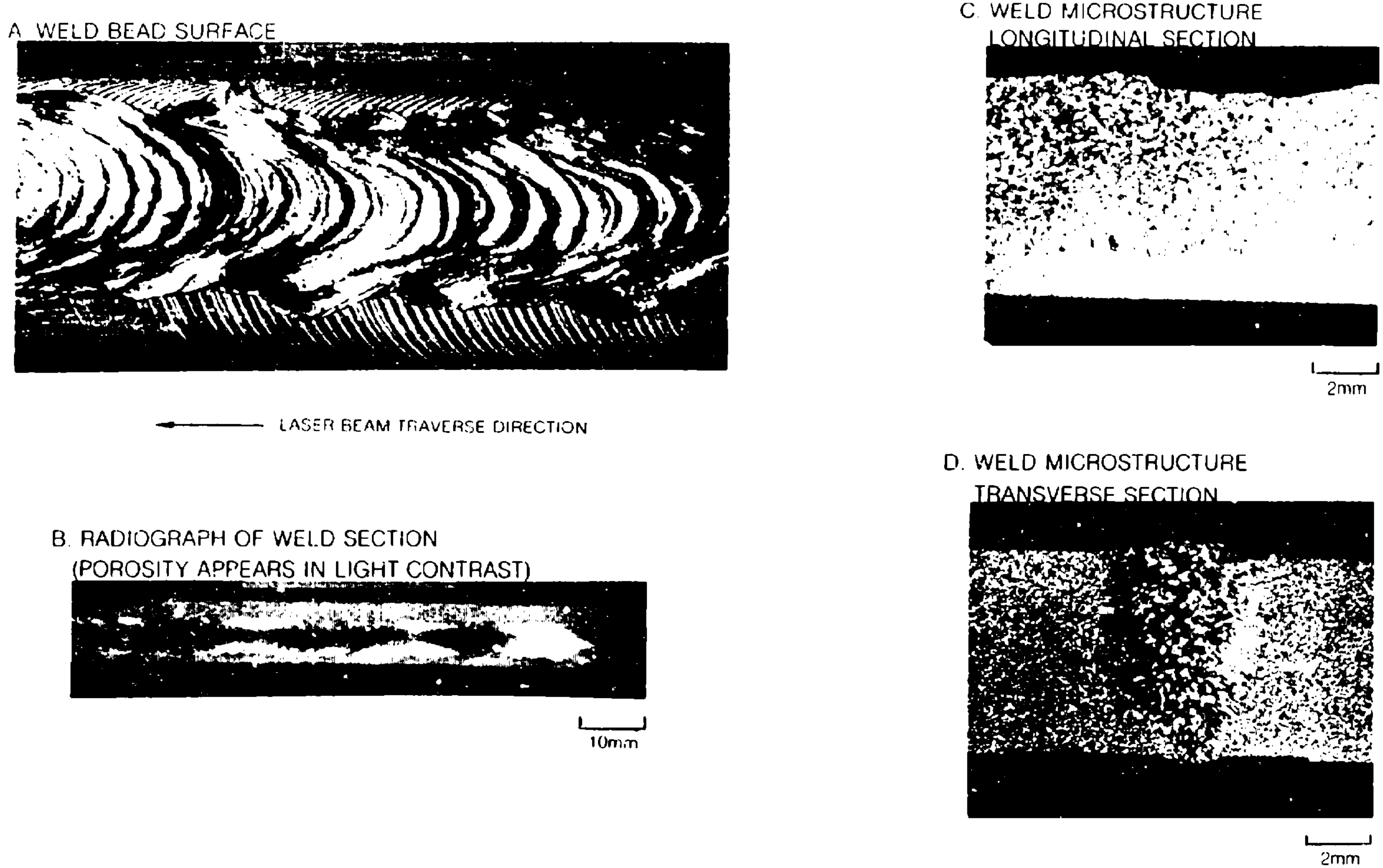


FIG. 3

STRUCTURE OF WELD 131-19

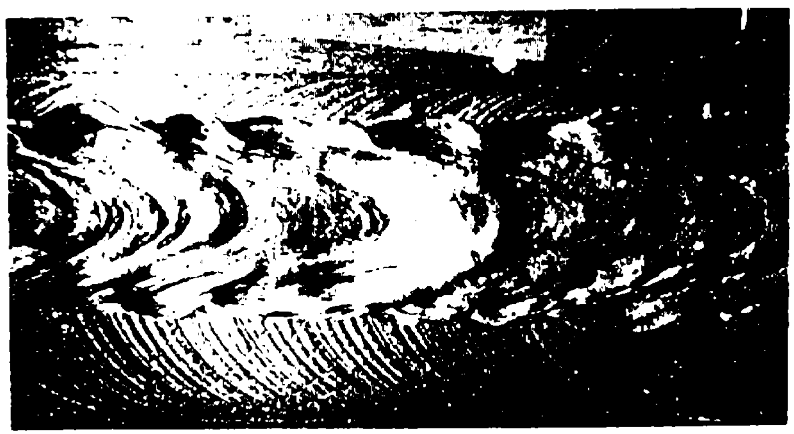
TABLE I, BEAD-ON-PLATE, 0.64cm, 5086, 7.0kW, 1.69cm/s, 1200 RPM



STRUCTURE OF WELD 131-18

TABLE I BEAD-ON-PLATE, 0.64cm 5086, 7.0kW, 2.0cm/s, 750 RPM

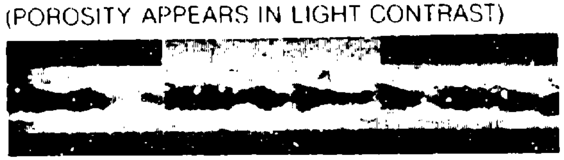
A WELD BEAD SURFACE



2mm

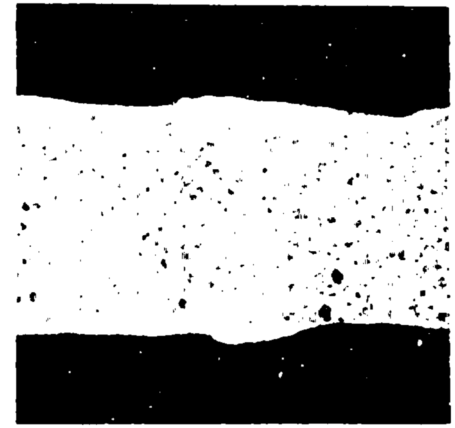
LASER BEAM TRAVERSE DIRECTION

B RADIOGRAPH OF WELD SECTION (POROSITY APPEARS IN LIGHT CONTRAST)

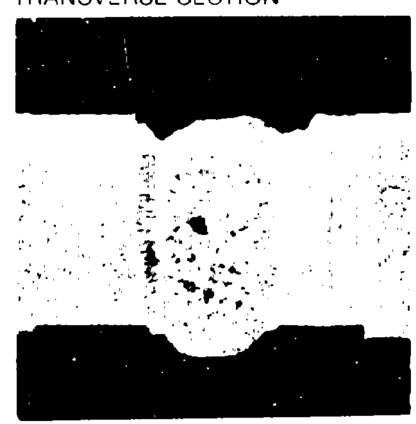


10mm

C WELD MICROSTRUCTURE LONGITUDINAL SECTION



D WELD MICROSTRUCTURE TRANSVERSE SECTION



2mm

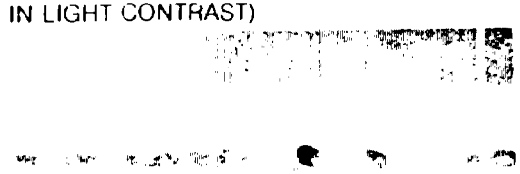
STRUCTURE OF TWO-SIDED BUTT WELD USING ROTATING BEAM

1.27cm PLATE, 5086, 6.4kW, 2.96cm/s, 2200 RPM, CROSS FLOW SHIELD, 0.57 m^3/hr HELIUM, 0.14m^3/hr ARGON

A. WELD BEAD, TOP SURFACE (FIRST PASS)

← LASER BEAM TRAVERSE DIRECTION

B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

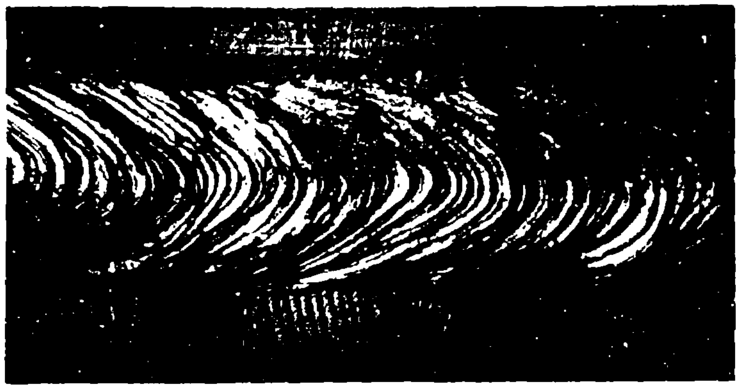


C. WELD MICROSTRUCTURE
TRANSVERSE DIRECTION

STRUCTURE OF TWO-SIDED BUTT WELD USING ROTATING BEAM

1.27cm PLATE, 5086, 5.5kW, 2.12cm/s, 2200 RPM, CROSS FLOW SHIELD: [illegible] m^3/hr HELIUM, 0.57m^3/hr ARGON

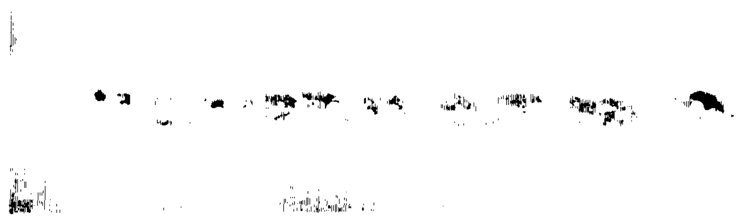
A. WELD BEAD, TOP SURFACE, (FIRST PASS)



← LASER BEAM TRAVERSE DIRECTION

2mm

B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)



10mm

C. WELD MICROSTRUCTURE
TRANSVERSE SECTION

2mm

FIG. 7

STRUCTURE OF WELD 131-25

TABLE II BEAD ON PLATE 0.64cm 5356 7.0kW ... 250 RPM

A WELD BEAD SURFACES

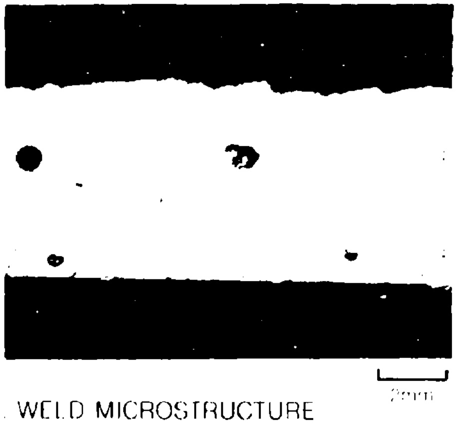
TOP SURFACE

BOTTOM SURFACE

⟵ LASER BEAM TRAVERSE DIRECTION

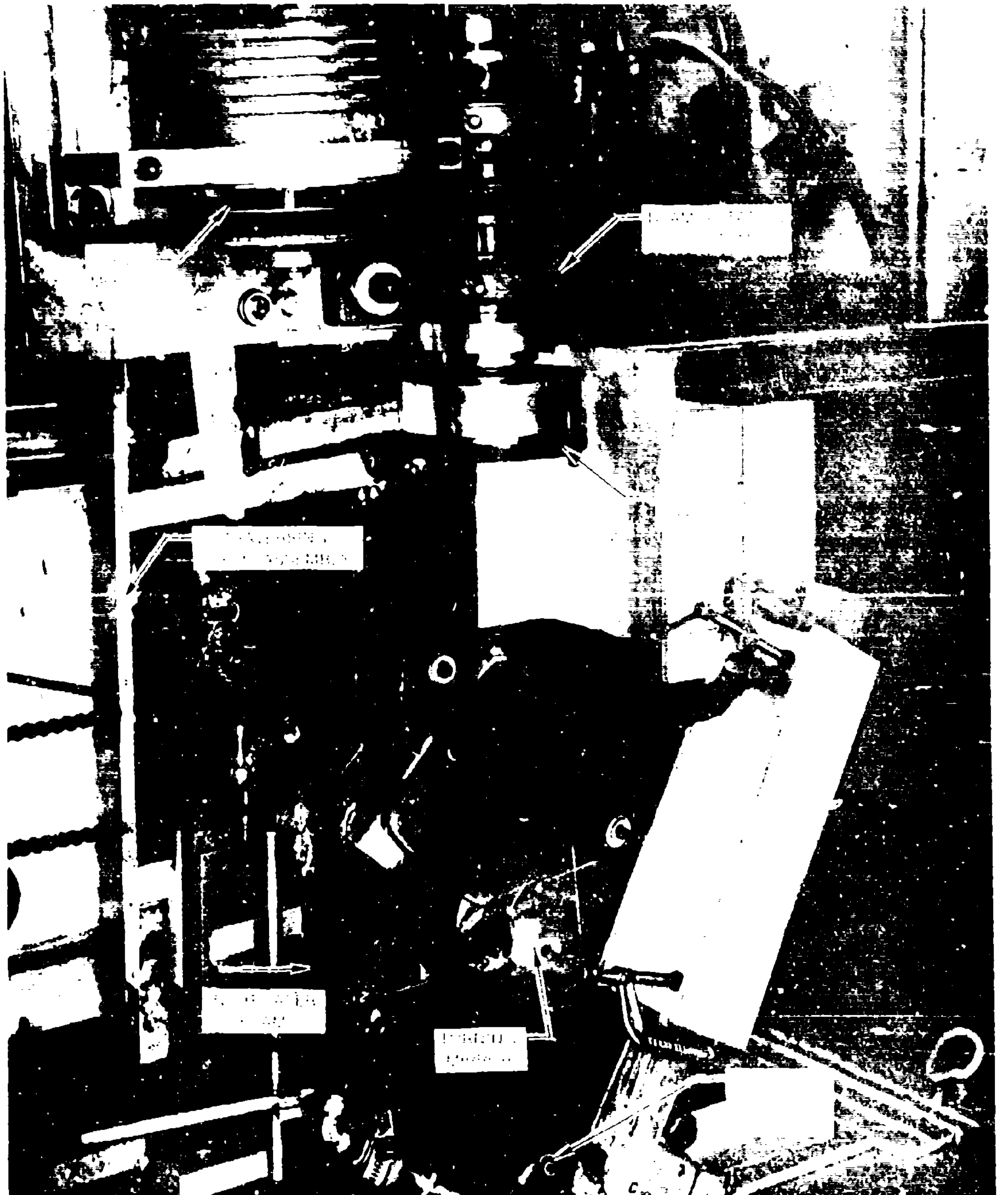
B RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

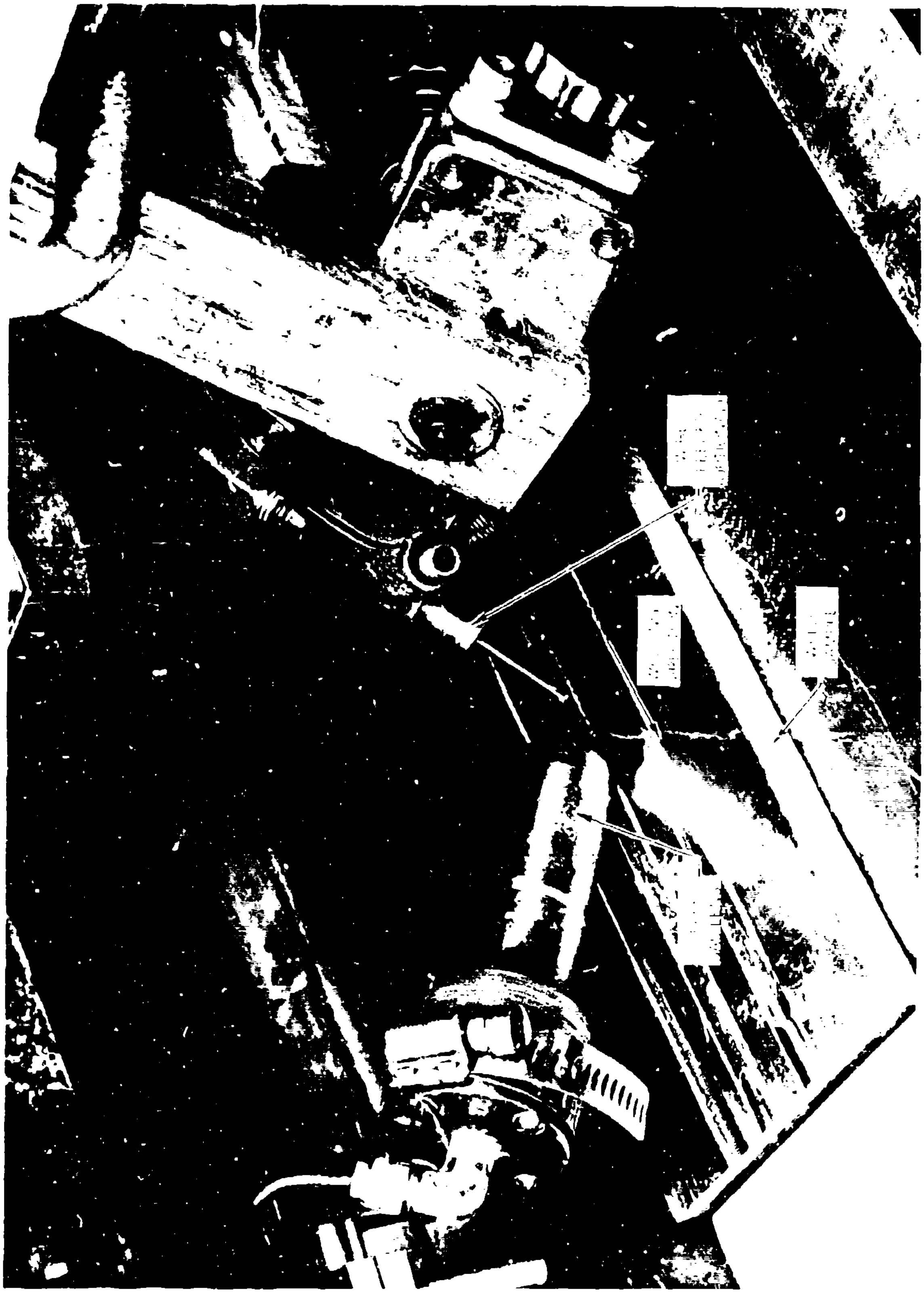
C WELD MICROSTRUCTURE
LONGITUDINAL SECTION



D WELD MICROSTRUCTURE
TRANSVERSE SECTION

LASER WELD STATION



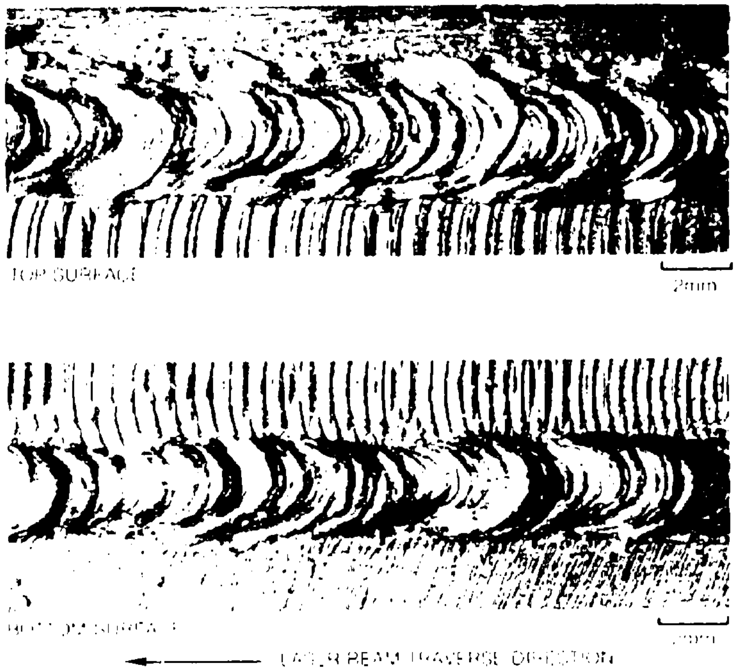


LASER BEAM/WELD SPECIMEN INTERACTION REGION

STRUCTURE OF WELD 2-2

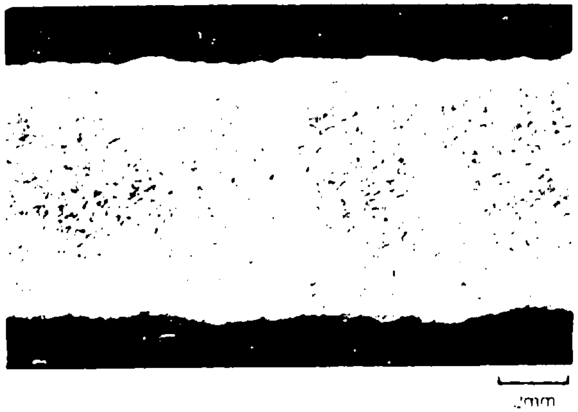
TABLE VI BEAD ON PLATE 0.64 cm, 5086, 7.0 kW, 1.48 cm/s, 3000 RPM, WIRE SPEED = 3.81 cm/s, 5.66m³/hr He

A WELD BEAD SURFACES

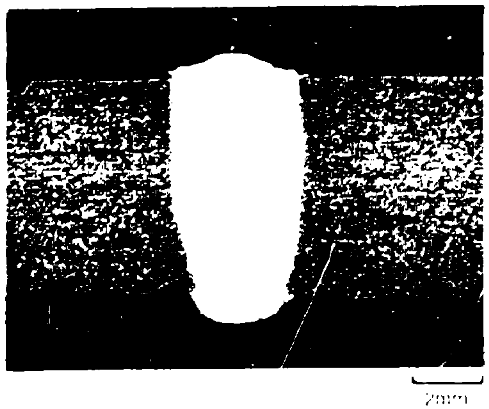


B RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

C WELD MICROSTRUCTURE
LONGITUDINAL SECTION



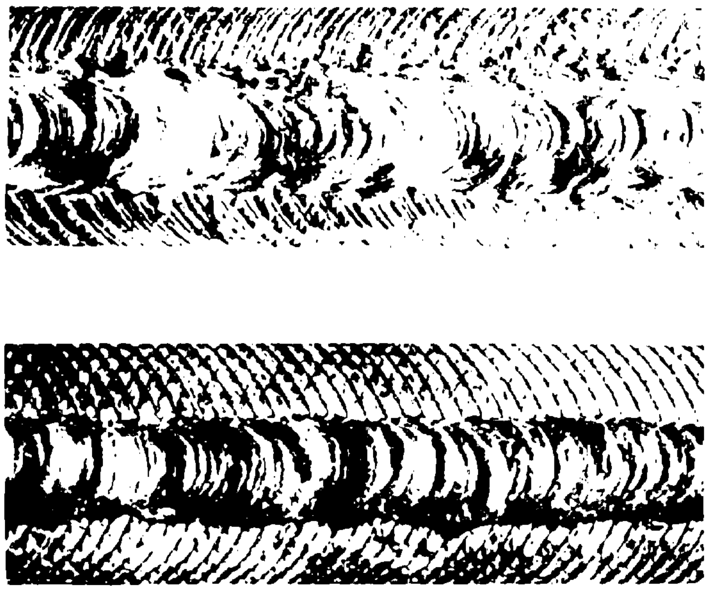
D WELD MICROSTRUCTURE
TRANSVERSE SECTION



STRUCTURE OF WELD 1-II

TABLE VI BEAD-ON-PLATE 0.64 cm. 5086 7.0 kW. 1.27 cm/s. 3000 RPM WIRE SPEED 4.23 cm/s. 5.66m^3/hr He

A WELD BEAD SURFACE



BOTTOM SURFACE

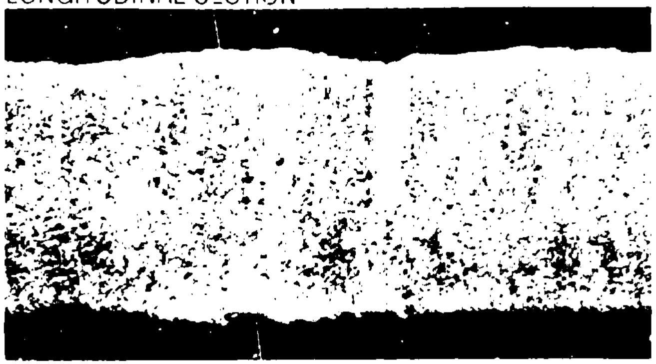
2mm

LASER BEAM TRAVERSE DIRECTION

B RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

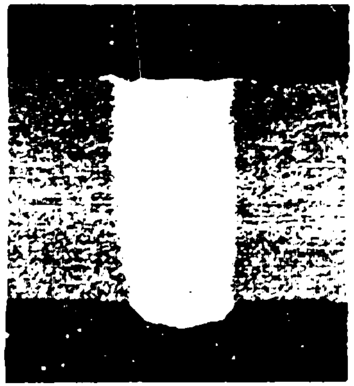
10mm

C WELD MICROSTRUCTURE
LONGITUDINAL SECTION



2mm

D WELD MICROSTRUCTURE
TRANSVERSE DIRECTION

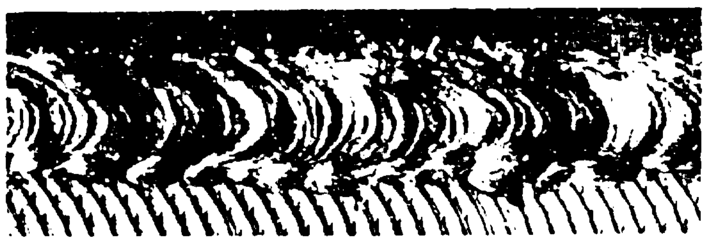


2mm

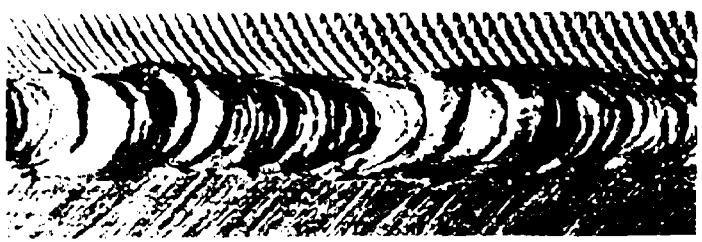
STRUCTURE OF WELD 1-12

TABLE VI BEAD-ON-PLATE 0.64cm 5086 7.0kW 1.48cm/s 3000 RPM WELD SPEED = 4.23cm/s 5.66m^3/hr He

A WELD BEAD SURFACES



TOP SURFACE

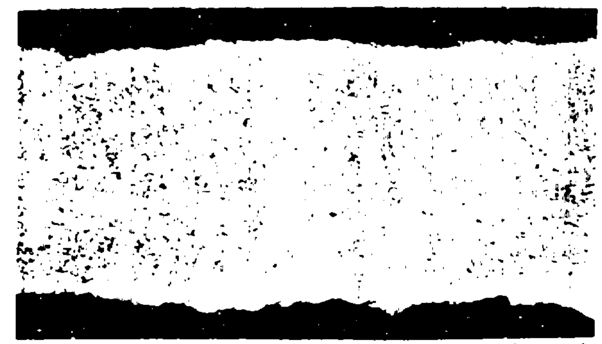


BOTTOM SURFACE

← LASER BEAM TRAVERSE DIRECTION

B RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

C WELD MICROSTRUCTURE
LONGITUDINAL SECTION



D. WELD MICROSTRUCTURE
TRANSVERSE DIRECTION

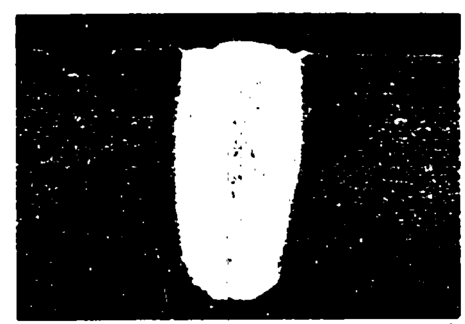
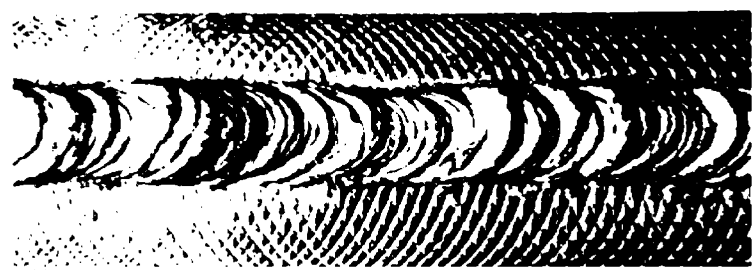


FIG. 13

STRUCTURE OF WELD 1-8

TABLE VI BEAD-ON-PLATE 0.64cm 5086 7.0kW 1.27 cm/s 3000 RPM WIRE SPEED = 2.12 cm/s 5.66m³/hr He

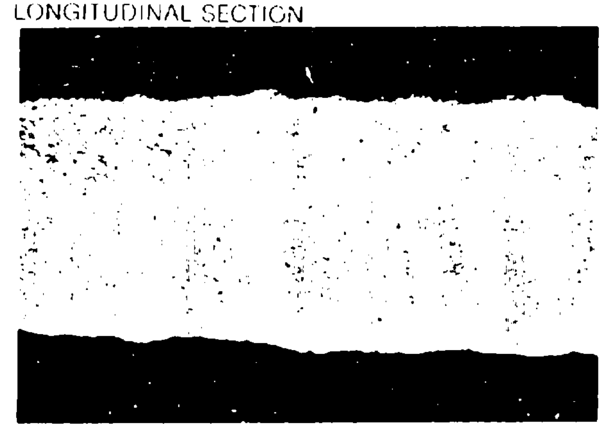
A. WELD BEAD SURFACES



LASER BEAM TRAVERSE DIRECTION

B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

C. WELD MICROSTRUCTURE
LONGITUDINAL SECTION



D. WELD MICROSTRUCTURE
TRANSVERSE SECTION

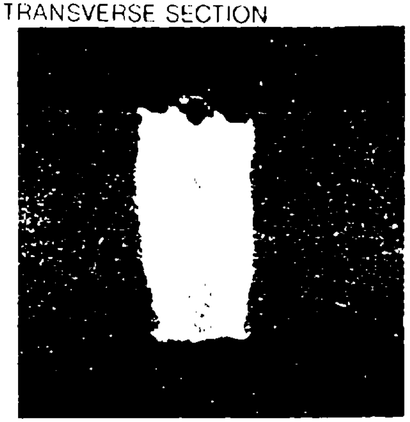
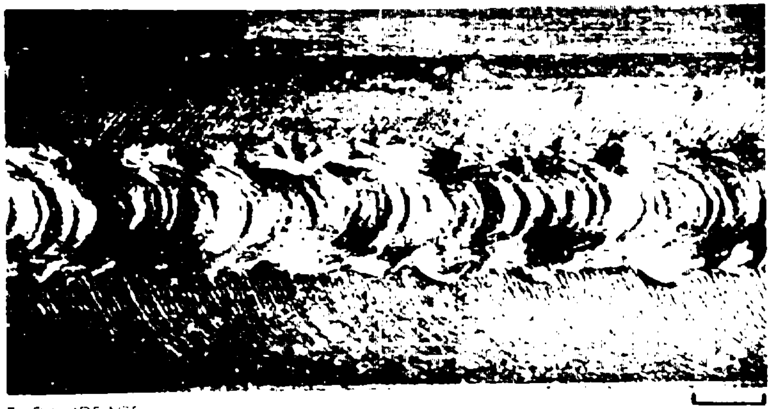


FIG. 14

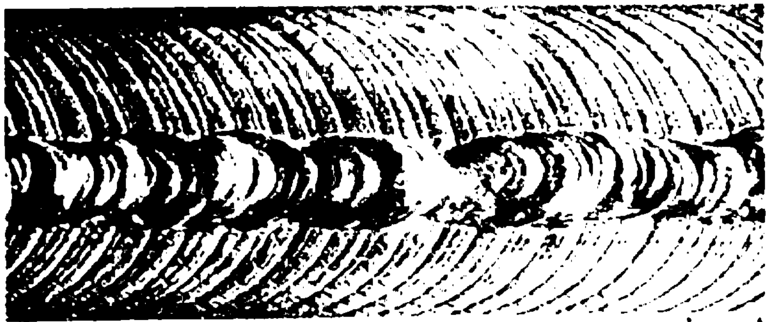
STRUCTURE OF WELD 1-13

TABLE V BEAD-ON-PLATE 0.64cm 5086, 7.0kW, 1.69cm/s, 3000 RPM WIRE SPEED = 4.23cm/s, 5.66m^3/hr He

A WELD BEAD SURFACES



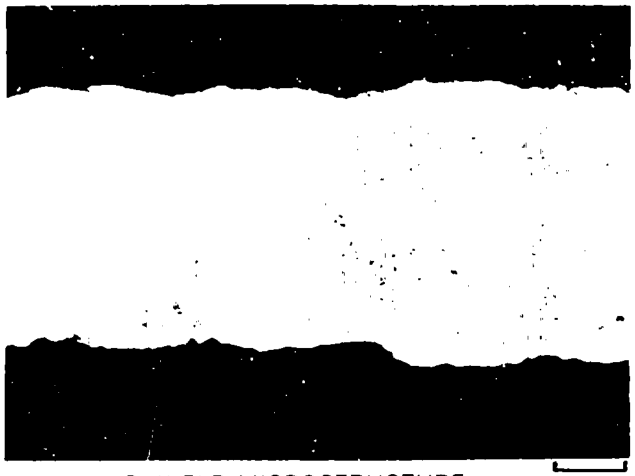
TOP SURFACE



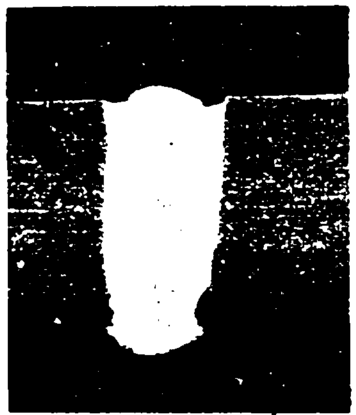
BOTTOM SURFACE ← LASER BEAM TRAVERSE DIRECTION

B RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)

C WELD MICROSTRUCTURE
LONGITUDINAL SECTION



D WELD MICROSTRUCTURE
TRANSVERSE SECTION



79-08-72-14

FIG. 15

STRUCTURE OF WELD 2-3

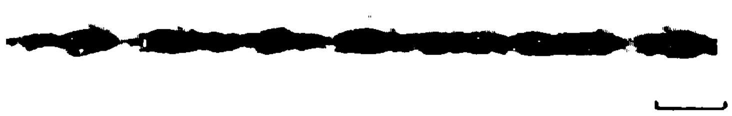
TABLE VI. BEAD-ON-PLATE 0.64cm 5086 7.0kW 1.27 cm/s 3000 RPM WIRE SPEED = 6.35 cm/s 5.66 m^3/hr He

A. WELD BEAD SURFACES

BOTTOM SURFACE

← LASER BEAM TRAVERSE DIRECTION

B. RADIOGRAPH OF WELD SECTION
(POROSITY APPEARS IN LIGHT CONTRAST)



C. WELD MICROSTRUCTURE
LONGITUDINAL SECTION